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Iron-Garnet Magnetic Field Sensors with 100pT/√Hz Noise-Equivalent Field

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The sensitivity of Faraday-effect sensors incorporating diamagnetically substituted yttrium iron garnet (YIG) is potentially much higher than of sensors employing pure YIG. Results of Faraday rotation linearity and sensitivity measurements are presented for gallium-substituted YIG. At 500 Hz, the noise-equivalent magnetic field is approximately 100pT/√Hz.

Introduction

Fiber-optic magnetic field sensors based on the Faraday effect in ferrimagnetic iron garnets exhibit much greater sensitivity than similar Faraday-effect sensors based on more conventional diamagnetic materials.[1] Recently, measurements made with yttrium iron garnet ($Y_3Fe_5O_{12}$, also known as YIG) exhibited a noise floor of 10 nT / √Hz and a flat frequency response to frequencies greater than 500 MHz.[2] Other iron garnets, however, should perform even better, particularly in terms of sensitivity. For ferrimagnetic Faraday-effect sensor materials, including the iron garnets, the sensitivity is ideally given by the ratio of the saturation Faraday rotation, $\theta_{F,sat}$, to the product of the demagnetization factor, N_D, and the saturation magnetization, M_{sat}. As shown in Fig. 1, the sensitivity at 1.3 μm of a YIG sample 5 mm in diameter and 3 mm in length is ≈ 0.7 deg/mT.

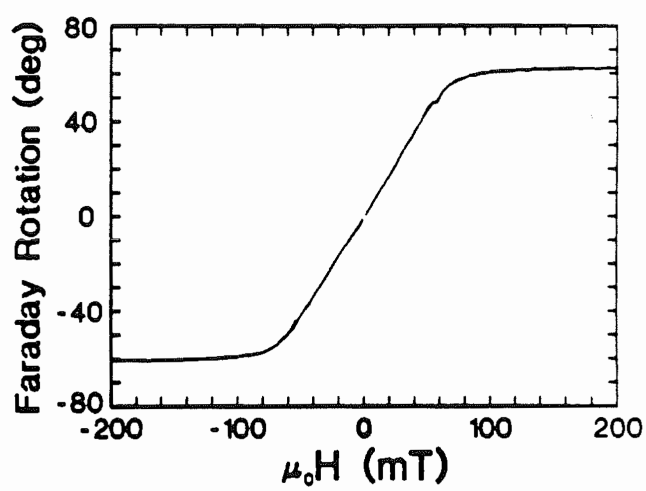

Figure 1. Dependence of Faraday rotation on applied magnetic field for pure YIG sample 3 mm long and 5 mm in diameter.

We have found that, by substituting an appropriate number of diamagnetic ions, such as Ga^{3+}, for certain Fe^{3+} ions in YIG, the sensitivity is substantially increased. Such an increase is apparently caused by a shift in the balance between the magnetic sublattices which determine both $\theta_{F,sat}$ and M_{sat}.[3] This idea was first used to improve the performance of magneto-optic light modulators.[3,4] For magnetic field sensing, this method of tailoring the magnetic and magneto-optic properties permits the measurement of smaller magnetic fields.

Properties of Gallium-Substituted YIG

The composition of gallium-substituted YIG is generally written $(Y)_3[Fe_{2-x}Ga_x](Fe_{3-y}Ga_y)O_{12}$, where x and y refer to the amount of gallium substitution in the octahedral and tetrahedral sublattices, respectively. The specific distribution of the gallium ions among the octahedral and tetrahedral sites influences both the magnetic[5,6] and magneto-optic[7] properties, and is itself partly dependent on the sample's thermal history.[6] For the specific sample[8] for which we obtained results, $x+y \approx 1$ and $M_{sat} \approx 24$ kA/m (in Gaussian units, $4\pi M_{sat} \approx 300$ G). This composition was chosen because of previous reports that it produced a significant increase in the ratio, $\theta_{F,sat}/M_{sat}$, compared with pure YIG.[3] More specifically, this substitution was found to reduce M_{sat} by about 85% (compared to YIG) while only reducing $\theta_{F,sat}$ by about 35% (at 1.52 μm). The sample was 1 mm in diameter and 3 mm in length, and thus had an approximate demagnetization factor of 0.109.[9]

Results

The Faraday rotation was measured as a function of applied magnetic field using a chopped source, an electromagnet, a differential detection system and a lock-in amplifier. The source was a laser diode which emitted 1.3 μm radiation. The data, shown in Fig. 2, were taken over one entire cycle of the magnetic field. The data exhibit a well-defined linear region between ± 1

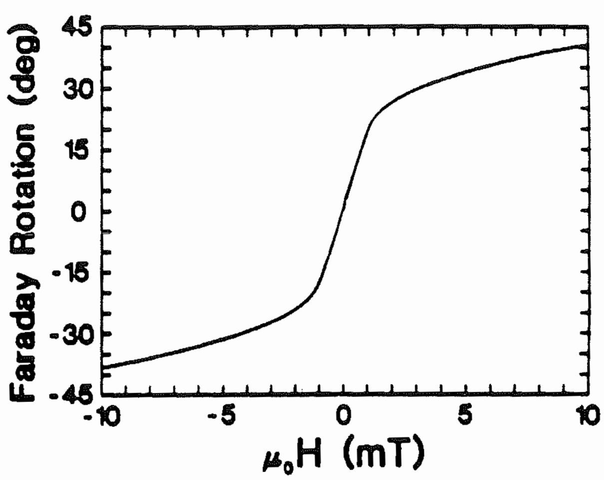

Figure 2. Dependence of Faraday rotation on applied magnetic field for gallium-substituted YIG sample 3 mm long and 1 mm in diameter.

mT with negligible hysteresis. The slope of the linear region is approximately 20 deg/mT. For fields greater than 1 mT, the slope decreases sharply but does not approach zero within the limits of the plot. This behavior is unlike that of pure YIG,[2] shown in Fig. 1, which exhibits a linear response bounded by well-defined saturation regions that have zero slope.

The noise-equivalent magnetic field was measured using the apparatus described in Ref. 2. An ac magnetic field of magnitude $\mu_0 H = 10^{-7}$ T (rms) and frequency 500 Hz was applied to the sample with Helmholtz coils. The dual outputs of a differential detection system were fed to an analog differential amplifier which was connected to a signal analyzer. The equivalent noise bandwidth of the signal analyzer was 0.187 Hz. The data are shown in Fig. 3. The signal-to-noise ratio is approximately 68 dB which produces a value of the noise-equivalent magnetic field of approximately 100 pT/√Hz. This figure represents a substantial (~100-fold) improvement over the previous best noise-equivalent magnetic field obtained with pure YIG.[2]

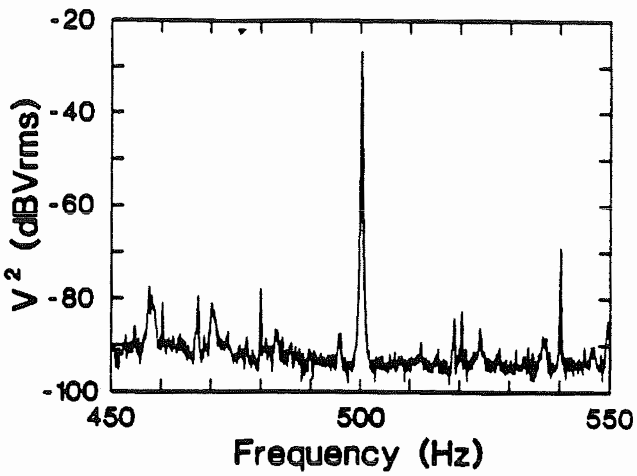

Figure 3. Spectral noise data obtained with gallium-substituted YIG sample exposed to 10^{-7} T rms, 500 Hz, magnetic field. The noise-equivalent magnetic field is ≈ 100 pT/√Hz.

Conclusion

Substituted iron garnets constitute a class of materials with widely tunable magnetic and magneto-optic properties which make them suitable elements for Faraday-effect magnetic field sensors. Specifically, certain diamagnetic substitutions in yttrium iron garnet reduce M_{sat} much more than $\theta_{F,sat}$. This results in a significant increase in sensitivity. For magnetic field sensing, these materials should also display a linear dependence of Faraday rotation on applied magnetic field with no significant hysteresis. Gallium-substituted YIG appears to satisfy these requirements while exhibiting substantially greater sensitivity than YIG.

Other iron garnet compositions, however, should be even more sensitive. For example, certain bismuth-substituted iron garnets have much greater values of $\theta_{F,sat}$ than YIG or gallium-substituted YIG.[10] If such materials were additionally "designed" to have small values of M_{sat}, their sensitivity could far exceed the results reported here.

References

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8. Sample grown by Deltronic Crystals, Inc. of Dover, New Jersey. This does not constitute a recommendation or endorsement. Samples from other suppliers may perform as well or better.

9. See, for example, D. J. Craik, Structure and Properties of Magnetic Materials (Pion Limited, London, 1971), p. 22.

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